Feature Article

The Olympic motto through the lens of equestrian sports

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Implications

- Horses are exceptional athletes that compete in a wide range of sports each requiring a unique combination of speed, power, balance, and gymnasticism.
- There are three Olympic equestrian sports each requiring distinct and different athletic attributes.
- Together, horse and rider combinations competing in Olympic equestrian sports fulfill the Olympic values of faster, higher, and stronger.

Key words: centre of mass, dressage, eventing, horse, jumping, mechanical energy

Introduction

The Olympic motto *Citius, Altius, Fortius* (faster, higher, stronger) was adopted with the launch of the Olympic movement in 1894. It was modified by the International Olympic Committee in 2021 with the addition of the word *Communiter* (together) to emphasize the importance of unity and solidarity in sport and in the World in general. This article interprets the Olympic motto in the context of the three Olympic equestrian sports in which a horse and a rider perform together as a single entity.

In this review, we describe and compare equine locomotor biomechanics in the context of the three Olympic equestrian sports: three-day eventing, show jumping and dressage, each requiring different athletic talents. Eventers gallop at an average speed of approximately 34 kmh^{-1} for 10 min across natural terrain negotiating inclines, declines, and turns and jumping up to 42 obstacles. Biomechanical requirements prioritize speed and strength. Physiologically, a large aerobic capacity limits lactate accumulation and delays the onset of fatigue, while having a muscle fiber profile that facilitates the development of force and power is necessary for jumping at speed. Show jumpers jump a course of approximately 12 obstacles that are 1.45–1.60 m high over 450–650 m at an average speed of 24 kmh^{-1}. The ability to generate large forces and high powers is needed to project the horse high enough to clear the fences. Show jumping is energy-intensive and horses have elevated blood lactate values at the end of a round. Dressage horses perform gymnastic movements at different gaits and over a range of speeds (0-22 kmh^{-1}) but with a low average speed (~8-9 kmh^{-1}) (Clayton, 1990). Heart rates are generally within the aerobic range and muscular effort appears to be localized to specific muscles that perform eccentric-concentric contractions to maintain the required uphill posture and balance while generating high force and power to perform the movements. In this article, we use the galloping performance of the event horse, the jumping performance of the show jumper, and a slow speed dressage movement requiring great strength and balance to explore how the equine athlete fulfills the Olympic values of faster, higher, and stronger.

The Equine Athlete

In a standing horse, the COM is located longitudinally at the level of the 13th thoracic dorsal spinous process, approximately 2 cm below the hip joint and about 1 cm left of midline (Figure 1) (Buchner et al., 2000). As a consequence of the head and neck being cantilevered out in front of the horse, the COM is closer to the forelimbs which carry 58% of body weight compared with 42% in the hindlimbs (Hobbs et al., 2014).

The hind and forelimbs display functionally important conformational differences. The angled joints of the hindlimbs flex during early stance controlled by eccentric action of the extensor muscles which then undergo powerful concentric contractions to provide propulsion. The forelimbs have less angulated joints and the loaded carpus locks in an extended position which allows the forelimb to act as a strut to adjust the speed and direction of travel, as well as the height and trajectory of the forequarters. The orientation of the stifle, which points forwards, and the elbow which points rearwards, is indicative of the directional compliance of the limbs (Lee and Meek, 2005), such that the hindlimbs provide propulsion and

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the forelimbs provide braking. Additionally, the hindlimbs accommodate almost 90% of the propulsive musculature, most of which are hip extensors (Payne et al., 2005).

During locomotion, the feet press against the ground to generate concurrent ground reaction forces (GRF) in 3-dimensional patterns that propel the horse's body. The timing, magnitude, direction, and point of application of concurrent limb GRFs have an overall effect in translating the COM and causing trunk rotation around the COM. The most obvious of these is pitching rotation such that the withers become relatively higher (upwards or uphill) or lower (downwards or downhill) than the croup. Horses adjust not only the GRFs, but also the

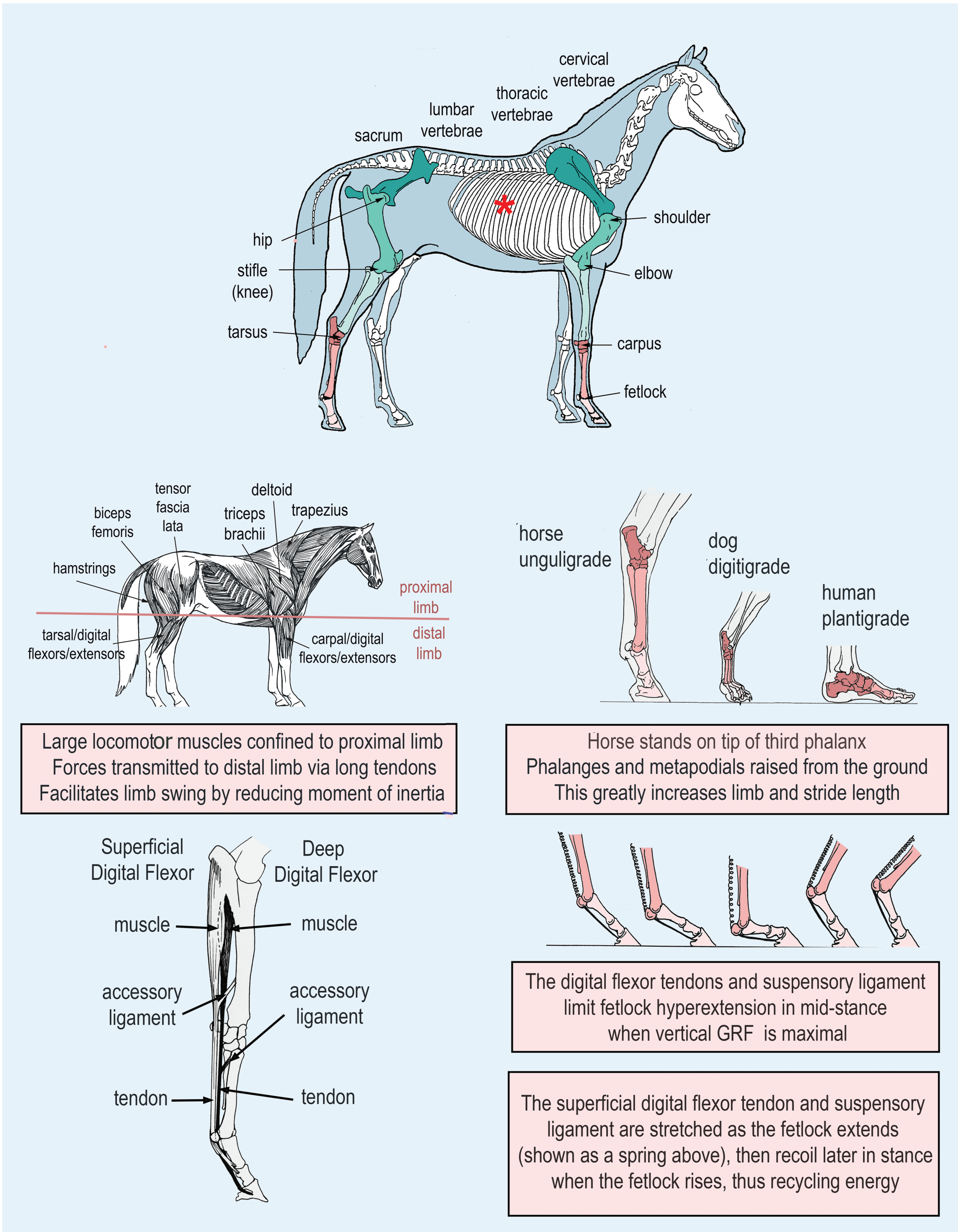

Figure 1. Overview of equine skeletal anatomy and factors that contribute to the horse's cursorial ability and energetic efficiency. * indicates center of mass position. Line drawings kindly provided by Sport Horse Publications.

timing of limb movements and hoof contact positions to maintain balance and control of the trunk angle (Figure 2) (Hobbs et al., 2016).

Eventing Cross Country

Eventing was developed for testing and selecting cavalry horses by simulating challenges the horse and rider would confront on and off the battlefield. The modern format consists of three phases (dressage, cross country, and show jumping). The cross country phase consists of galloping over undulating terrain, turning, and jumping up to 42 obstacles within an optimum time. Specifications for the Olympic Games state a maximal distance of 5,800 m at an average speed of 9.5 ms^{-1} including jumping 38–42 fences. The requirements are reduced if there are concerns about the horses' health in the prevailing conditions. At Tokyo 2021, for example, the distance was reduced from 5,700 to approximately 4,500 m due to excessive heat and humidity.

It is common for elite event horses have some Thoroughbred ancestry since this breed has, for centuries, been bred to gallop. Maximal speed of a racing Thoroughbred is around 71 kmh^{-1} (~20 ms^{-1}) though eventers travel at only about half that speed due to the relatively long distances over which they compete, and the inclusion of frequent turns and jumping efforts (Figure 3).

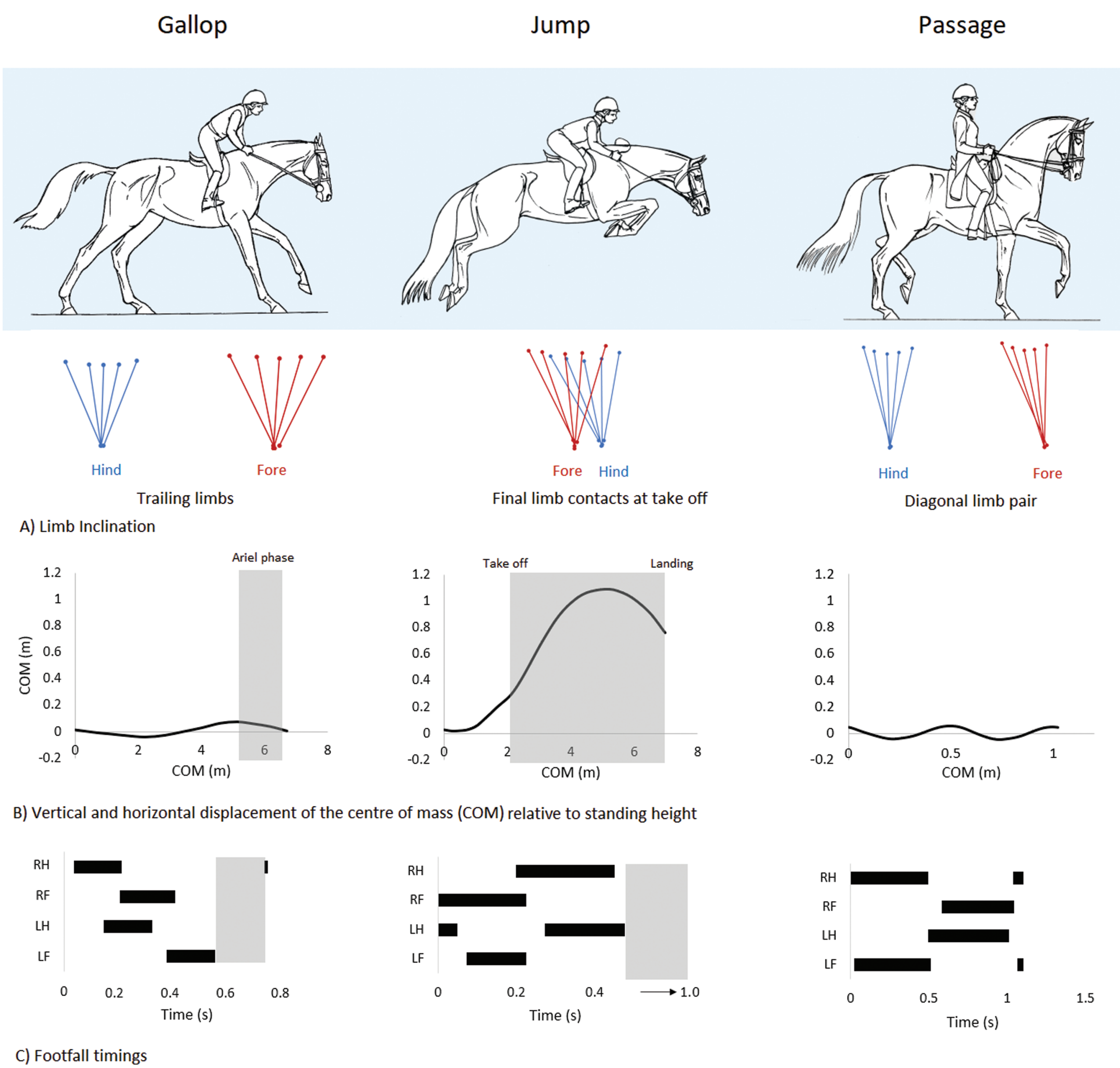

Figure 2. Kinematic data from one stride of an event horse at gallop at 10 ms^{-1}, a show jumping horse clearing a 1.40 m square oxer and one stride from a dressage horse performing passage. All data are described moving towards the right. (A) Limb inclination during the stance phase from the spine of scapula to the hoof (fore) and the greater trochanter to the hoof (hind) for the trailing limbs at gallop, for the leading limbs during jumping approach (fore) and take off (hind) and for a diagonal pair of limbs during passaging. (B) Center of mass trajectory in the vertical and horizontal directions (m) and (C) footfall patterns showing the stance phase timings (s) in black during each movement. Line drawings kindly provided by Sport Horse Publications.

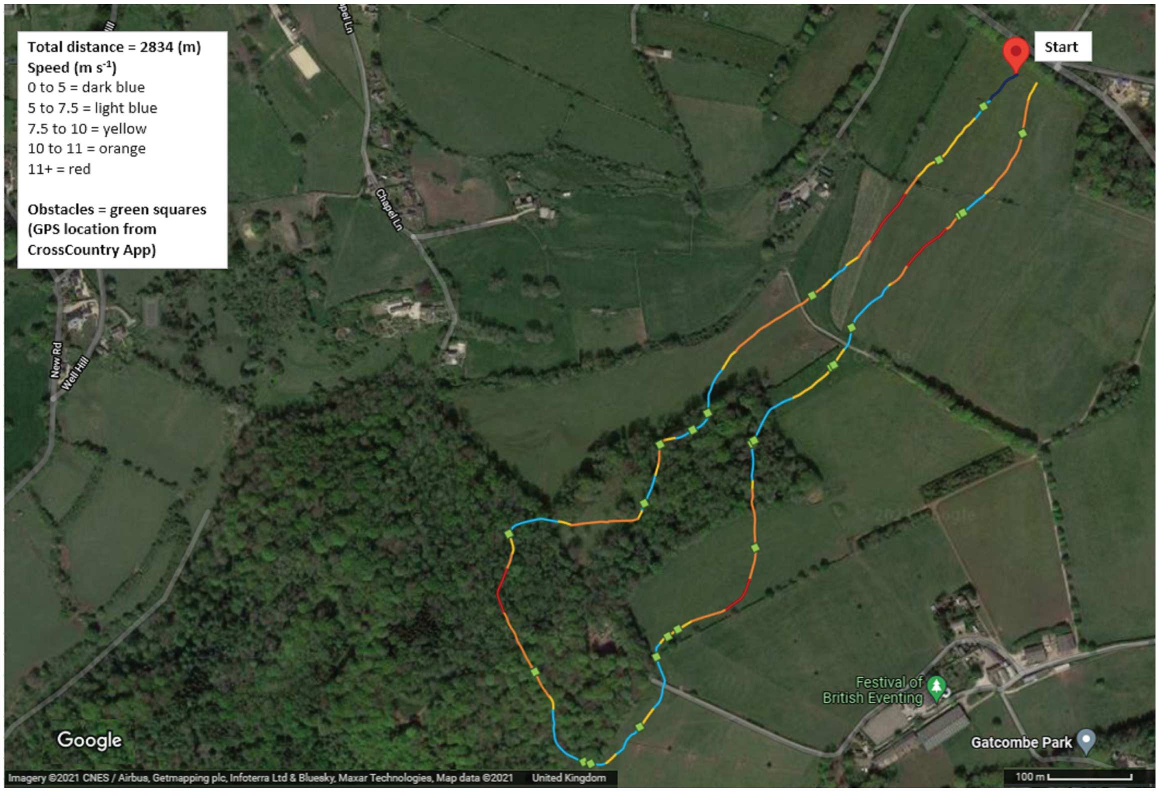

Figure 3. Speed (Polar Equine V800) from one horse negotiating a British Eventing novice cross country course (Cameron-Whytock, PhD thesis, University of Central Lancashire).

The demands of galloping, jumping, and turning for several minutes require an enormous physiological effort that exceeds the anaerobic threshold at least during part of the course (Amory et al., 1993).

Our focus for this section is on the gallop

Kinematics. At the gallop, each limb contacts the ground separately with the hind and forelimb contacts occurring as couplets; the first limb of the couplet to contact the ground is designated the trailing limb and the second is the leading limb. The leading limb is on the same side of the body for both limb pairs. The footfall sequence is trailing hind (TrH), leading hind (LdH), trailing fore (TrF), and leading fore (LdF) followed by an aerial phase (Figure 2).

At moderate speeds, changes in stride length are the primary means of adjusting speed. An increase in speed is achieved by moving the body further over the grounded limbs and reducing overlaps between limb contacts (Witte et al., 2006) through modulation of hip and shoulder torques (Herr and McMahon, 2001). As speed increases, limb stance durations shorten, further reducing overlap times.

Cross country courses include clockwise and anti-clockwise turns. Horses generally lead with the limbs on the inside of the turn which facilitates maintenance of balance. Turning speed is limited by the radius of the turn, the maximum capacity of the limbs to produce force and friction/traction between the hoof and the ground (Tan and Wilson, 2011). Horses change between the left and right leads to negotiate turns or to reduce fatigue. The lead change is initiated by the forelimbs followed by the hindlimbs half a stride later (Leach, 1987).

Kinetics. In ridden Thoroughbreds galloping at 11.4 ms^{-1}, peak vertical GRFs normalized to body mass are TrH: 13.6 N/kg, LdH: 12.3 N/kg, TrF: 14.0 N/kg, and LdF: 13.6 N/kg (Self Davies et al., 2019a). Vertical impulse has been reported to be equally distributed between the hind and forelimbs during galloping (Self Davies et al., 2019a), which is in contrast to other gaits in which the forelimbs have higher impulses.

When stance duration decreases at high speed, the limbs have less time to generate GRFs so they press against the ground more forcefully to maintain the necessary impulse and, consequently, peak GRFs increase. This is associated with increased hyperextension of the carpal and fetlock joints, predisposing to repetitive strain injuries to the superficial digital flexor tendon, which supports the extensor aspect of both carpus and fetlock, and the suspensory ligament which supports the extensor aspect of the fetlock. These structures have a relatively high content of elastic tissue that tends to accumulate degenerative changes over time, making them particularly susceptible to injury in middle-aged and older equine athletes (Thorpe et al., 2010).

COM control. A good event horse must be gallop efficiently around the cross country course. Mechanical energy is used as external work that transports the COM relative to the environment and internal work to cycle the limbs back and forth relative to the COM. Overall, the cost of transport, which is the amount of metabolic energy consumed to cover a given distance during galloping, is very low (Piccione et al., 2013).

The galloping horse achieves dynamic balance using momentum to carry the body forwards, whereas the sequential limb contacts generate GRFs that raise the body in opposition to gravity and maintain forward momentum. Since each hoof contacts the ground separately, the task of reorienting body motion from forward-downward to forward-upward is divided among four separate limb collisions which reduces the loss of momentum and results in large energy savings (Ruina et al., 2005). Other mechanisms, including elastic energy recycling by tendons in the limbs and back, further reduce the mechanical energy cost (Ruina et al., 2005) and contribute to the remarkable efficiency of galloping. External work done by the limbs to move the COM is considerably less than the internal work used for limb pro-retraction (the pendular range of motion of the limbs from a cranial to a caudal position). Published values for internal work and metabolic costs for galloping yield an apparent muscular efficiency of 37–46%, which would be reduced by energy storage in limb tendons (Self Davies et al., 2019b).

The COM follows a sinusoidal path with one oscillation per stride (Figure 2); it is lowest when the peak vertical GRF summed over all limbs is maximal, which occurs during overlap of the LdH and TrF stance phases, and highest during the aerial phase. The COM range of vertical motion decreases curvilinearly with speed from 18.5 cm at 7 ms^{-1} to 8.9 cm at 17 ms^{-1} (Pfau et al., 2006). Excessive vertical oscillations are energetically expensive but some bouncing motion is needed to take advantage of energy recycling by elastic tendons (Minetti et al., 1999).

Show jumping

Show jumping is one of the most popular equestrian sports and has been included in every Olympic Games since 1912. Most of the top jumping horses are European Warmbloods, which combine size, strength, and athleticism. Physically, the horses must be strong and powerful to project themselves high into the air.

The sport involves jumping a course of fences in a specified order. Penalties accrue for knocking down a fence, refusing to jump a fence, failing to clear the width of a water jump, or exceeding the time allowed which is based on a minimal required speed. Maximal fence sizes at the Olympic Games are 1.7 m high, 4.0 m wide (water jump), 2.2 m wide (triple bar), or 2.0 m wide (other fences). As fence materials become increasingly lighter, the horse's ability to assess fence dimensions during the approach is crucial to developing appropriate linear and angular momentum at take-off so all parts of the body clear the fence and land safely on the other side.

Kinematics. During the approach, the stride is adjusted to take off at an appropriate distance from the fence. During their final contact, the forelimbs act as struts; the carpal joints lock into the close-packed position that aligns the forearm and metacarpus. The horse's body vaults over the forelimbs rotating the trunk and raising the forequarters which puts the body in an appropriate orientation for hindlimb push off. The ability to raise the forequarters is a predictor of success in clearing water jumps (Colborne et al., 1995).

The two hindlimbs push off almost synchronously and equidistant from the fence during a stance phase of ~220 ms. In the first half of hindlimb stance, the hip joints extend by about 25° which has the effect of continuing the upward rotation. At the same time, flexion of the stifle and tarsus by 40° results in the COM being lowered by 0.05 m. The hip, stifle, and tarsus then extend, vertical and horizontal trunk velocities increase, and the direction of trunk rotation changes (Bogert et al., 1994).

The jump stride includes an aerial phase between hindlimb lift-off and forelimb contact during which the horse jumps the fence as the trunk rotates downwards with almost constant angular velocity (Galloux and Barrey, 1997). The distal limbs are drawn up close to the body to facilitate clearance of the jump and the lumbosacral joint extends as the hindquarters pass over the fence. Correct coordination of these movements is essential for all parts of the body to clear the fence.

At landing, the first limb to contact the ground is the TrF which is almost vertical and has a short stance duration as the horse rolls forward onto the LdF. The LdH has a longer stance duration and the position of the TrH limb at landing is highly variable (Clayton and Barlow, 1991).

Kinetics. During forelimb contact prior to take-off, considerable energy is dissipated then regenerated and, although some energy is recycled in elastic tendons, a large muscular contribution is required to provide the necessary forces to elevate the forehand (Bobbert and Santamaría, 2005). Peak vertical GRF is higher in the TrF, and in both forelimbs the longitudinal GRF is almost exclusively braking. This raises the forequarters and rotates the trunk upwards (Schambardt et al., 1993).

Peak vertical GRFs are smaller in the hindlimbs than the forelimbs but stance durations are longer facilitating generation of large vertical impulses (Schamhardt et al., 1993). The longitudinal force is primarily propulsive in nature and the GRF vector is caudal to the COM throughout stance which reverses trunk rotation to downwards during the aerial phase (Bobbert and Santamaría, 2005). Power is absorbed across the hindlimb joints as they flex in early stance then, in the last 60% of hindlimb stance, large muscular forces straighten the joints (Figure 4), the pelvis rises, and power is generated to launch the horse into the aerial phase. The stifle joint produces 85% of the work done by the hindlimbs (Dutto et al., 2004). During the final 60%, the hip, tarsal, and fetlock joints generate positive work to raise the body, which increases the horse's potential energy. Most of the energy required to clear the fence is produced during hindlimb push off and has been estimated to be 59,000 W in horses jumping a fence 1.5 m high (Bogert et al., 1994).

At landing, the TrF has a higher peak vertical GRF than any other limb combined with a propulsive longitudinal GRF during its short stance phase. The LdF has a longer stance duration, a somewhat lower peak vertical GRF and the longitudinal GRF is primarily braking. The net effect

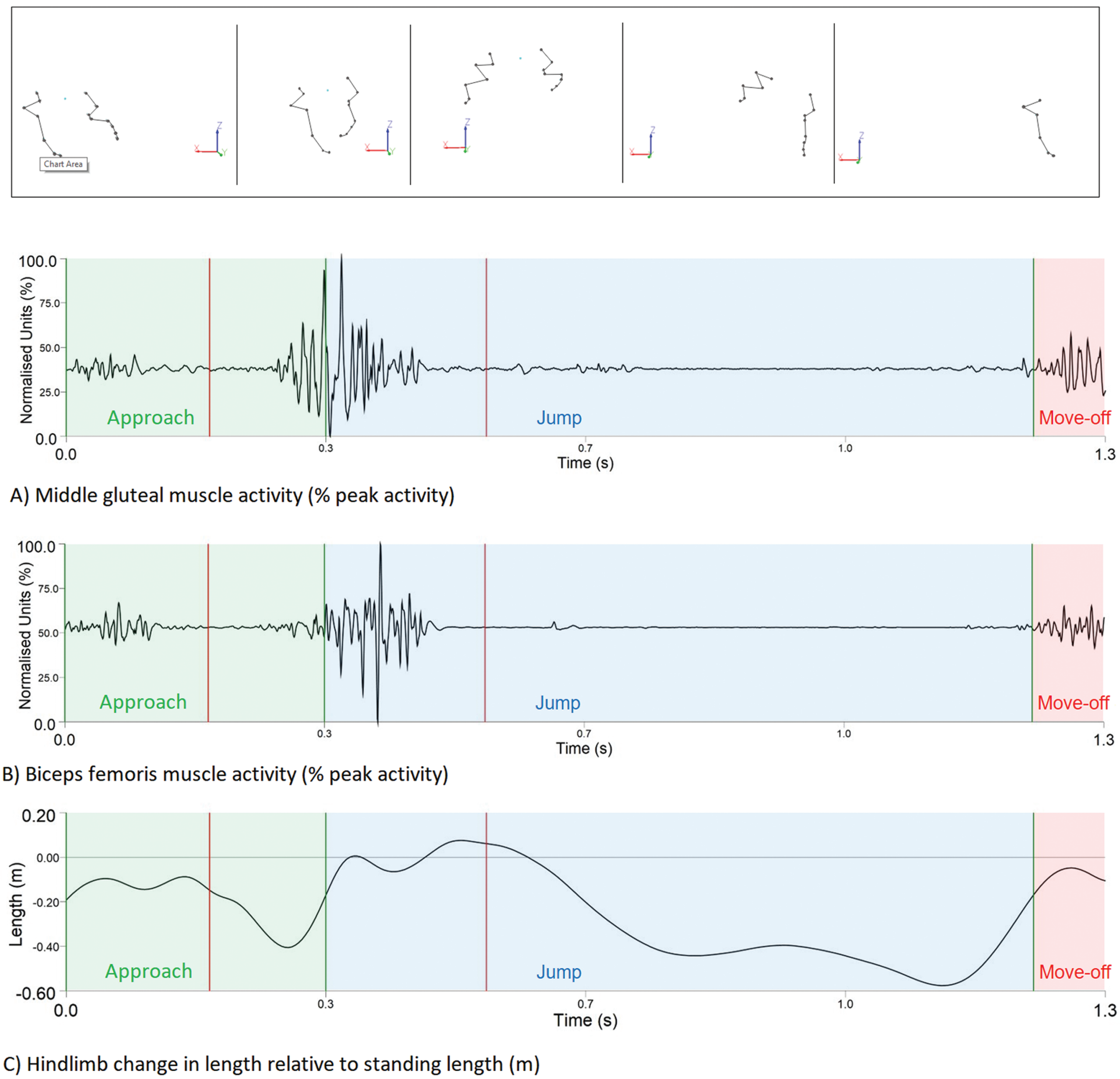

Figure 4. Muscle bursts collected using surface electromyography EMG from (A) middle gluteal and (B) biceps femoris muscles (% peak), and (C) corresponding hindlimb shortening (m) from a horse jumping a 1.2 m square oxer (St George, PhD thesis, University of Central Lancashire).

is to reverse the forward-downward motion of the COM, reverse the direction of trunk rotation, and push the horse away from the fence (Schamhardt et al., 1993). The hindlimbs provide vertical and mainly propulsive forces that restore forward velocity and balance (Schamhardt et al., 1993).

Calculated forces in TrF are highest in the suspensory ligament but change very little with fence height, whereas forces in the superficial digital flexor tendon increase with increasing fence height bringing the tendon increasingly closer to its failure limit (Meershoek et al., 2001). A study of sport specific injuries (Murray et al., 2006) confirmed that the forelimb superficial and deep digital flexors in elite show jumpers are both at a higher risk of tendinitis compared to those of general-purpose horses. In addition to fence height, this was partly attributed to the accumulation of degenerative changes with aging in elite horses. That said, the suspensory ligament is still reported to be most frequently injured in jumping horses (Murray et al., 2006) and suspensory branch subclinical abnormalities are common in elite show jumping horses (Read et al., 2020).

COM control. Considerable energy is expended to overcome inertia each time the direction of COM movement changes at take-off or landing. The cost of transport to negotiate a course of 13 fences over a distance of 700 m is almost twice as high as the cost of galloping 2,100 m at an average speed of 700 $mmin^{-1}$ (Piccione et al., 2013).

During the aerial phase, the COM follows a parabolic trajectory determined by the forces prior to take-off. Coordinated movements of the body segments contribute to overall rotation with the trunk, hindlimbs, and head-neck segments being most influential (Galloux and Barrey, 1997).

The shape of the parabola changes with the profile and dimensions of the fence (Clayton et al., 2021). When jumping a vertical fence (1.60 m high) and a spread fence (1.50 m high ×1.80 m wide), horses had significantly higher COM vertical velocity, COM peak height, and average trunk angular velocity but significantly lower COM horizontal velocity compared with jumping a water jump (4.5 m wide). The trunk was most elevated at take-off for the vertical fence. Peak height of the COM trajectory coincided approximately with the mid-point of the spread fence profile was toward the take-off side of the water jump and toward the landing side for the vertical fence.

The height to which the COM can be raised is limited by the horse's muscular capacity. In one study (St George et al., 2021), horses showing the greatest COM elevation when jumping a 1 m fence had significantly shorter contraction times for the middle gluteal muscle at take-off, which was correlated with a faster speed of approach, more rapid hindlimb shortening, and a shorter hindlimb stance duration at take-off (Figure 4).

The high-jump world record for a horse is 2.47 m (8 ft 1 in). Established in 1949, it is one of the longest-running unbroken sport records in history, suggesting that it is close to the limit of equine jumping ability.

Dressage

Dressage is a judged sport in which horses perform gymnastic exercises showing different gaits, speeds, and directions of movement. In the sport of dressage, the ascending levels of competition challenge the horse to show a larger number of gaits and movements that require an advanced level of balance and muscular control, while performing in a progressively uphill posture. High-level dressage horses are predominantly European Warmbloods.

In contrast to galloping in which economy of movement is paramount, dressage horses are rewarded for performing with great impulsion which uses energy beyond that needed to complete the task. This over-rides the neuromotor drive to minimize energy expenditure.

They are trained to walk, trot, and canter at speeds below and above those that normally trigger transitions to a different gait. Here, we consider a gait called passage that is a slow trotting movement in which the diagonal limb pairs appear to hover when they are elevated during the swing phase.

Kinematics. Passage is a learned movement performed only at the highest levels of dressage competition. Similar to trot, limb movements are diagonally synchronized, and diagonal stance phases alternate with aerial phases. Passage is performed at a speed of 1.2–1.9 ms^{-1}, which is below the speed at which horses typically transition to walk. Compared with a slow collected trot, passage has significantly longer stride and stance durations, shorter stride length, smaller limb pro-retraction, and the limbs show increased elevation in the swing phase.

Horses maintain an uphill posture throughout the stride. The hind hoof contacts the ground before the diagonal forelimb which is regarded as both a consequence of and a contributor to uphill posture (Hobbs et al., 2016).

Kinetics. The long stance durations in passage allow generation of the necessary impulses without high peak GRFs (Figure 5). In the hindlimbs, the transition from braking to propulsive GRF occurs early in stance which facilitates generating large hindlimb propulsive impulses. Together with predominantly vertical GRF from the forelimb during single support in terminal stance, these GRFs contribute to a COM moment to raise the forequarters (Clayton and Hobbs, 2017). Since the GRFs are predominantly propulsive in the hindlimbs and braking in the forelimbs, their vectors converge through most of diagonal stance, which is thought to assist in maintaining balance.

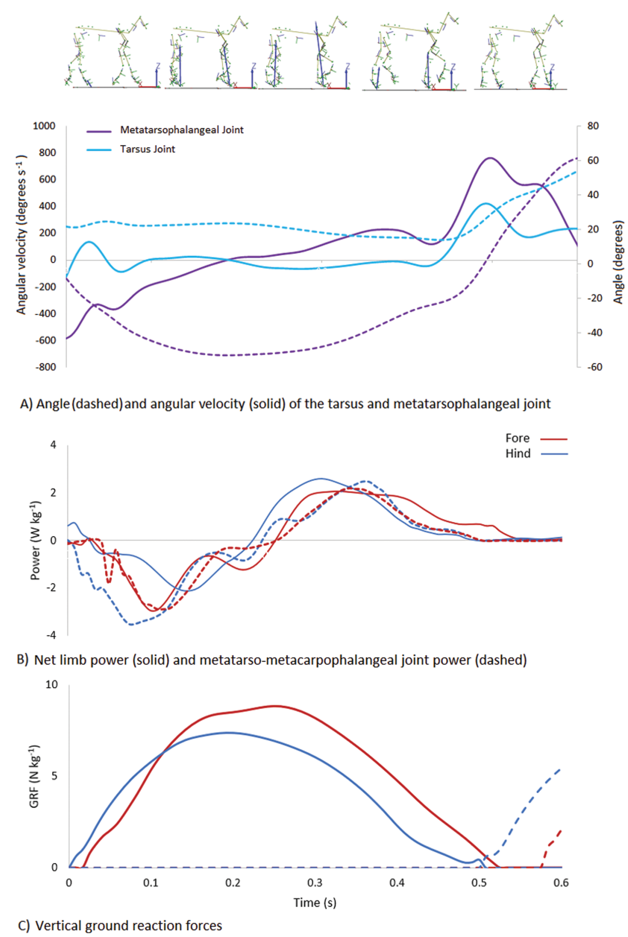

Figure 5. Diagonal stance phase from one horse performing passage. (A) Joint angles (degrees) and angular velocities (degrees s-1) from the tarsus and metatarsophalangeal joint, (B) net power production and power production from metacarpophalangeal and metatarsophalangeal joints (W kg-1), and (C) corresponding vertical ground reaction forces (N kg^{-1})

COM control. The coordinated GRFs of the hind and forelimbs maintain forward progression, provide vertical COM motion, and control trunk orientation (Hobbs and Clayton, 2013). The slow speed of passage challenges the horse's ability to control pitching moments and maintain equilibrium. This is achieved using a combination of kinematic and kinetic adjustments involving coordinated changes in GRF magnitudes, GRF distribution between synchronously loaded limbs, and changes in hoof placements longitudinally to adjust the moment arms of the vertical GRFs.

Due to the slow speed of passage and the small range of pro-retraction of the limbs, it is speculated that the distal limb contribution to the development of muscular power to generate impulses to raise the COM is greater in passage than in trot (Figure 5). During the absorption phase, a combination of tarsal flexion and metatarsophalangeal hyperextension produces high strain in the suspensory ligament (Holmstrom and Drevemo, 1997). To produce sufficient power to raise the COM, the distal joints must rotate at a high angular velocity during the release of strain energy. This may, in part, contribute to the high incidence of hindlimb suspensory desmitis in dressage horses (Murray et al., 2006).

Dressage has seen large improvements in performance over the past 20 yr. The current Olympic record percentage total score of 84.666% was set in Tokyo in 2021. This, and record-breaking scores at other performance levels, indicates continuing improvements attributable to multiple factors including selective breeding, improvements in riding style, better equipment, and understanding the physiological requirements of the sport in relation to training techniques.

Conclusions

Eventers gallop at sub-maximal speeds on varied terrain whilst negotiating solid obstacles. They must be bold, agile, and able to gallop in an energetically efficient manner to meet the speed requirements. Show jumpers generate large GRFs and expend considerable energy to overcome inertia and change the body's trajectory both at take-off and landing in accordance with the profile and height of the fence. The fact that the high-jumping record has not been broken for many years suggests that it is at, or close to, the maximal height a horse can jump. Today's course builders construct technically difficult challenges with light materials to determine a winner rather than relying on fence size. It is difficult to evaluate changes over time in a judged sport like dressage but there seems little doubt that selective breeding of horses with appropriate temperament, conformation, and strength has raised the bar in dressage performance.

About the Authors

Hilary M. Clayton is Professor and McPhail Dressage Chair Emerita at Michigan State University. She earned veterinary and doctoral degrees from the University of Glasgow and worked in academia for over 45 yr in the United Kingdom, Canada, and the United States. Her research interests are in sport horse science and, more specifically, in equine locomotor biomechanics. She is an advocate for sustainable training and conditioning of equine athletes with the goals of maximizing performance and enhancing longevity in sport. She has extensive experience working with horses competing at the highest levels, including the Olympic Games, and acts as an advisor to national and international equestrian sport governing bodies. Since 2014 she has worked as an independent consultant within the equine industry.

Sarah Jane Hobbs is a Reader in Equine and Human Biomechanics at the University of Central Lancashire, where she also gained a BEng(Hons) Mechanical Engineering degree in 2000 and a PhD in equine biomechanics in 2007. Her PhD work involved developing instrumentation to measure internal hoof strain and using 3D motion capture techniques to track motion of the horse's forelimb. Since then she has collaborated on international studies, which include investigating fundamental aspects of balance and stability, exploring the functional consequences of uneven fore hooves, defining performance in dressage and exploring methods of analyzing continuous gait data. She is the Director of a Research Centre at the university, leading author on the FEI Equine Surfaces White Paper, and currently leading a project to evidence the FEI para-dressage classification system. Her interests span the kinetics and kinematics of equine gait, hoof-horse-surface interactions, muscle activity during movement, horse/rider interactions and hoof structure, growth and mechanics. Corresponding author: sjhobbs1@uclan.ac.uk

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